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Original article

Various performance-enhancing effects from the same intensity of whole-body vibration training

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Abstract

Purpose: The purpose of this study was to compare the effects of an 8-week whole-body vibration training program in various frequency and amplitude settings under the same acceleration on the strength and power of the knee extensors.

Methods: Sixty-four young participants were randomly assigned to 1 of 4 groups with the same acceleration (4 *g*): high frequency and low amplitude ($n = 16$, 32 Hz, 1 mm) group, medium frequency and medium amplitude ($n = 16$, 18 Hz, 3 mm) group, low frequency and high amplitude ($n = 16$, 3 Hz, 114 mm) group, and control ($n = 16$, no vibration) group. All participants underwent 8 weeks of training with body mass dynamic squats, 3 sessions a week.

Results: The results showed that the high frequency and low amplitude group increased significantly in isometric contraction strength and 120°/s isokinetic concentric contraction strength; the medium frequency and medium amplitude group increased significantly in 60°/s and 120°/s isokinetic strength of both concentric and eccentric contraction; and the low frequency and high amplitude group increased significantly in 60°/s and 120°/s isokinetic eccentric contraction strength.

Conclusion: All frequency and amplitude settings in the 8-week whole-body vibration training increased muscle strength, but different settings resulted in various neuromuscular adaptations despite the same intensity.

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Keywords: Isokinetic contraction strength; Muscle contraction speed; Neuromuscular adaptation; Vibration acceleration; Vibration amplitude; Vibration frequency

1. Introduction

Numerous reviews and meta-analyses indicated that acute vibration stimulation and/or chronic whole-body vibration (WBV) training could enhance muscle maximal strength and power.[1–4] The chronic effect of vibration has shown benefits in maximal voluntary contraction strength,[1] 1-repetition maximum,[4] and countermovement jump (CMJ) performances.[1,4] Vibration stimulation used in combination with other training methods, rather than vibration stimulation alone, was also considered to conduct more neuromuscular excitations and show more efficient training effects.[5–7] However, a previous study demonstrated that only the higher frequency of 50 Hz showed an increase of maximum muscle strength at an amplitude of 3 mm;[8] consequently, if the amplitude was increased to 10 mm, all frequencies of 30 Hz, 40 Hz, and 50 Hz showed a significant increase in electromyography (EMG) value for the vastus lateralis; the frequency of 30 Hz showed the greatest increase.[9] The greater EMG value could also be found with the greater amplitude at the fixed frequency of 30 Hz.[10] It seemed that WBV training had led to a better training effect for muscle strength with the greater amplitude but not necessarily with the higher frequency.[2,3]

The effects of WBV training could be determined by the vibration volume and intensity, which comprised the frequency,

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the amplitude, the duration of vibration stimulation, the rest interval, and the stiffness of muscle or joint of those who undertook vibration stimulation.[11–14] Furthermore, the acceleration of WBV training could represent the vibration intensity, which was dependent on the frequency and amplitude of the vibrating platform.[15] A previous study showed that if the acceleration ranged from 0.2 *g* to 9.0 *g*, the high-amplitude vibration was always associated with the greater EMG activity, and the effect of frequency was most marked at the higher amplitude with a moderately linear relationship with EMG activity.[16] Although the acceleration could be determined by the interaction between the vibration frequency and the amplitude of the platform, each of them induced a different mechanism of the neuromuscular system.

Higher frequency or greater amplitude, which represented the change in the number of stimulations or the muscle length, respectively, induced greater acceleration for increasing muscle activation, and, consequently, a better chronic training effect would be expected.[1,12] Nevertheless, acceleration was provided as only 1 of the characteristics of vibration platform use in most previous studies. One previous study indicated that the specific neuromuscular adaptation was possibly induced by different WBV training settings,[17] but there was no evidence showing whether it would relate to the strength and power of muscle contraction. Two serial studies determined that a setting of low frequency and high amplitude (15–30 Hz, 10 mm) with 4 min of vibration stimulation could temporarily enhance isometric contraction strength of the knee extensors, body balance, and CMJ performances; the effects were more significant than those in the high frequency and low amplitude (25–40 Hz, 2 mm) setting.[18,19] However, these studies did not control the same acceleration of vibration stimulation among the groups, and no chronic training effect was reported.

Therefore, the purpose of this study was to compare the effects of an 8-week WBV training period in various frequency and amplitude settings under the same acceleration on concentric and eccentric contraction strength and power of the knee extensors. The hypothesis was that the muscle strength and power of the knee extensors would increase significantly after an 8-week WBV training period, and different training effects would be expected owing to the different stimulated mechanisms of vibration frequency and amplitude on neuromuscular adaptations.

2. Materials and methods

2.1. Participants

Sixty-four healthy young people were recruited in this study (32 males and 32 females; age 20.1 ± 1.1 years; height 167.7 ± 9.5 cm; body mass 61.8 ± 11.6 kg). The inclusion criteria were age between 18 and 22 years and lack of WBV training experience. The exclusion criteria were a muscle or bone injury of the lower extremities and regular use of resistance training within the previous 6 months (to avoid any other training effects). The participants were required to be informed and to provide written consent before enrollment into this study. This study was approved by the Institutional Review Board of Taipei Medical University, Taiwan, China.

2.2. Study design

This study had a randomized controlled experimental design. A 4-group pre- and post-test design was used to examine the effects of an 8-week WBV training period with various frequency and amplitude settings under the same acceleration on concentric and eccentric contraction strength and power of the knee extensors. The 4 groups included a high frequency and low amplitude (HFV) group, a medium frequency and medium amplitude (MFV) group, a low frequency and high amplitude (LFV) group, and a control (CON) group. The intensity of WBV training in the HFV, MFV, and LFV groups was controlled at the same acceleration. An isokinetic dynamometer (System 3 Pro; Biodex, New York, NY, USA) was used to measure muscle strength of maximal voluntary isometric contractions and low and high isokinetic concentric and eccentric contractions of the knee extensors. The acceleration time of muscle contraction during each test was used to evaluate the power of the knee extensors.

All participants were assigned to 1 of the 4 groups randomly. Each group had the same number of men and women ($n = 16$, 8 men and 8 women). Ten participants dropped out because they were unable to participate in 2 or more consecutive training sessions. The final number of participants was 54 (13 in the HFV group, 15 in the MFV group, 15 in the LFV group, and 11 in the CON group). No significant differences were found in the anthropometric characteristics among the 4 groups (Table 1).

2.3. Training procedures

The HFV, MFV, and LFV groups underwent an 8-week WBV training period on a vibration platform with dynamic squat sessions 3 times per week. The same acceleration (4 *g*) was applied for each group, and various frequency and amplitude settings were calculated by the formula $g = A(2\pi f)^2/9.81$, where g is acceleration of vibration platform output, A is the amplitude, and f is the frequency.[15] To control the different frequency and amplitude settings with the same acceleration load, 3 different commercial models of WBV training platforms were used in this study: (1) HFV group: frequency, 32 Hz; amplitude, 1 mm;

Table 1
Participants anthropometric characteristics (mean ± SD).

	HFV ($n = 13$)	MFV ($n = 15$)	LFV ($n = 15$)	CON ($n = 11$)
Age (year)	20.6 ± 1.4	20.6 ± 1.3	19.3 ± 0.5	19.6 ± 0.5
Height (cm)	168.0 ± 12.3	167.6 ± 9.9	167.4 ± 8.2	167.7 ± 12.0
Body mass (kg)	62.5 ± 10.5	62.9 ± 9.4	61.3 ± 12.9	60.8 ± 16.3

Abbreviations: CON = control; HFV = high frequency and low amplitude; LFV = low frequency and high amplitude; MFV = medium frequency and medium amplitude.

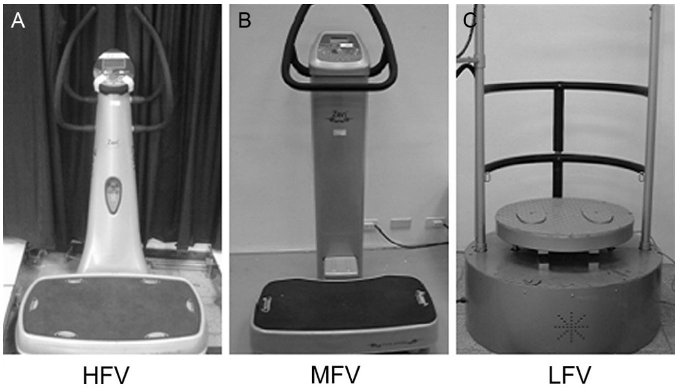

Fig. 1. Different whole-body vibration training platforms with the same acceleration (4 *g*). (A) high frequency and low amplitude (HFV, 32 Hz, 1 mm) setting; (B) medium frequency and medium amplitude (MFV, 18 Hz, 3 mm) setting; and (C) low frequency and high amplitude (LFV, 3 Hz, 114 mm) setting.

platform, Zen Pro TVR-6900 (Tonic Fitness Technology Inc., Taiwan, China); (2) MFV group: frequency, 18 Hz; amplitude, 3 mm; platform, Zen Pro TVR-4900 (Tonic Fitness Technology Inc.); and (3) LFV group: frequency, 3 Hz; amplitude, 114 mm; platform, PowerMaster CSU-750 (JoongChenn Industry Co., Ltd., Taiwan, China).[20] The vibration type of each WBV training platform was vertical (Fig. 1). To ensure that the frequency and amplitude settings of these WBV training platforms fulfilled the requirements of this study, an accelerometer was attached to the platform to measure the time from peak to peak, and the frequency was calculated as the reciprocal of that time period. A pencil was set on the platform to measure the highest and the lowest points of the platform's movement, and the difference between the 2 points was then used to calculate the amplitude of the platform. If the measured frequency and amplitude did not fulfill the requirement of the design, the platform manufacturer would adjust the mechanism until all requirements were satisfied. During the 8-week WBV training, all training platforms showed consistent measurement of frequency and amplitude.

Previous studies indicated that the amount of muscle activation for dynamic squats was significantly greater than that for static squats during WBV training.[21] Therefore, the participants underwent WBV training in a body mass squat training position with dynamic knee-flexion movement from 90° to 150°. A metronome was used to control the tempo of squatting to once every 2 s. The time for each set was 60 s with 2 min rest intervals between sets in the HFV, MFV, and CON groups. For the LFV group the dynamic knee-flexion movement was similar to that of a passive leg press, so the squat velocity was led by the platform. Thus, the training time of the LFV group was shortened to 20 s to maintain the same squat number. To satisfy the adaptation of conventional training principles, the training volume was progressive, and all groups were controlled with the same volume during the whole training period as well: 4 sets per session for Weeks 1 and 2; 5 sets per session for Weeks 3, 4, and 5; and 6 sets per session for Weeks 6, 7, and 8. The CON group performed the same dynamic knee-flexion movement as the HFV and MFV groups on the vibration platform at the same tempo, but no vibration stimulation was provided. All participants were prohibited to pursue any other training exercises during the entire training period.

2.4. *Test procedures*

Before and after the 8-week WBV training, the maximal voluntary isometric contraction strength, low (60°/s) and high (120°/s) isokinetic concentric and eccentric contraction strength, and acceleration time of all participants were measured within 1 week. A motor-driven isokinetic dynamometer (System 3 Pro) was used for all measurements. After warming up, participants were asked to sit on the seat of dynamometer with their shoulders, waist, and thighs fastened to the seat to reduce body movement. Next, the relative position of the seat and the dynamometer were adjusted to allow the rotation center of knee joint (i.e., the lateral femoral condyle) to align with the rotation axis of the dynamometer. Subsequently, the calibration of the gravitational center of the shank was conducted. The dynamometer setting was the same for each participant during the pre- and post-test. The test leg was the participant's dominant leg. The maximal voluntary isometric contraction strength was measured first. Participants were asked to extend their knee joint with a fixed 60° angle by their maximal voluntary contraction strength 2 times, each lasting for 3 s with a 1 min rest interval.

After a 30 min rest, the isokinetic concentric and eccentric muscle strength at different contraction speeds and the acceleration time were measured. The angular velocities were set at 60°/s and 120°/s. The participants were given a practice at 30% perceived strength 3 times before the formal test for every angular velocity to maximize performance, reduce injury potential, and become familiar with the test movement and speed. During the formal test, each participant completed 2 sets of 60°/s and 120°/s in random order and was asked to complete 3 repetitions. The maximal voluntary torque (N·m) and the shortest acceleration time (ms) of 2 sets were used for statistical analyses. The acceleration time was the time required for the angular velocity to reach isokinetic conditions (60°/s, 120°/s) from 0°/s. According to previously published methods, the shorter acceleration time indicated better muscle power.[22]

2.5. *Statistical analyses*

SPSS software Version 18.0 (SPSS Inc., Chicago, IL, USA) was used for statistical analyses. The test–retest reliability of each dependent variable was assessed by intraclass correlation coefficients (ICCs) of pre- and post-test values. For the maximal voluntary torque and acceleration time analyses, a two-way analysis of variance (ANOVA) for repeated measures (4 groups × 2 times) was used to assess significant changes between the pre- and post-tests. Tukey's method was used for *post hoc* comparisons in cases where ANOVA showed statistically significant differences, with the significant level set to $p < 0.05$.

3. Results

3.1. *Test–retest reliability*

The acceleration time of the knee extensors showed moderate test–retest reliability (ICCs: 0.526–0.773), and the maximal voluntary torque, for which ICC values were always greater than 0.700 (0.878–0.938), provided evidence of substantial reliability.

3.2. Maximal voluntary torque

There were no differences between the groups regarding the maximal voluntary isometric torque of the knee extensors before training ($p > 0.05$). After an 8-week WBV training period, the HFV and CON groups experienced significantly larger maximal voluntary isometric torque of knee extensors than did the LFV group ($p < 0.05$, Table 2). Moreover, the HFV group showed a significant increase of 17.6% ($F(1, 12) = 12.390$, $p < 0.05$), and the CON group also showed a significant increase of 17.6% ($F(1, 10) = 11.723$, $p < 0.05$).

There were no significant differences between the groups regarding the maximal voluntary isokinetic torque of the knee extensors before and after an 8-week WBV training period ($p > 0.05$, Table 2). However, after an 8-week WBV training period, the HFV group showed a significant increase of 35.8% in 120°/s isokinetic concentric contraction torque ($F(1, 12) = 24.564$, $p < 0.05$); the MFV group showed significant increases of 13.8%, 13.5%, 25.8%, and 24.7% in 60°/s and 120°/s isokinetic concentric and eccentric contraction torques ($F(1, 14) = 16.569, 5.164, 41.683, 23.617$, $p < 0.05$), respectively; and the LFV group showed significant increases of 7.6% and 15.6% in 60°/s and 120°/s isokinetic eccentric contraction torques ($F(1, 14) = 5.507, 11.921$, $p < 0.05$), respectively.

3.3. Acceleration time

There were differences between the groups regarding the acceleration time of the knee extensors before training ($p < 0.05$), so the pre-test values were selected as covariates for further statistical analyses. After an 8-week WBV training period, the HFV and MFV groups had a significantly smaller acceleration time of 60°/s isokinetic concentric contractions of the knee extensors than did the CON group ($p < 0.05$, Table 2). Moreover, the CON group showed a significant increase of 14.7% ($F(1, 10) = 9.831$, $p < 0.05$).

After an 8-week WBV training period, the HFV group had a significantly shorter acceleration time of 60°/s isokinetic eccentric contractions of the knee extensors than did the MFV and LFV groups ($p < 0.05$, Table 2). Moreover, the HFV group showed a significant decrease of 12.7% ($F(1, 12) = 8.116$, $p < 0.05$), and the LFV group showed a significant increase of 19.3% ($F(1, 14) = 11.041$, $p < 0.05$).

After an 8-week WBV training period, there were no significant differences between the groups regarding the acceleration time of 120°/s isokinetic concentric and eccentric contractions of the knee extensors ($p > 0.05$, Table 2). However, the HFV group showed a significant decrease of 9.2% in the acceleration time of 120°/s isokinetic concentric contractions ($F(1, 12) = 14.606$, $p < 0.05$); the LFV group showed a significant increase of 21.2% for the acceleration time of 120°/s isokinetic eccentric contractions ($F(1, 14) = 6.971$, $p < 0.05$).

4. Discussion

In contrast with previous studies regarding the chronic effect of WBV training, this study used the same acceleration (i.e., training intensity) to compare the effects of various frequency and amplitude settings. Previous studies showed that the mean frequencies of the vertical platform test for chronic strength and power training were 33.66 Hz and 31.79 Hz,[2,3] respectively, so the frequency for the HFV group was set at 32 Hz in this study. Moreover, a higher amplitude for the HFV group would lead the

Table 2
Maximal voluntary torque of knees extensors.

	HFV ($n = 13$)		MFV ($n = 15$)		LFV ($n = 15$)		CON ($n = 11$)	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post
Maximal voluntary torque (N·m)								
Isometric	171.7 ± 63.9	196.2 ± 56.8*#	174.0 ± 45.2	184.3 ± 46.3	169.5 ± 56.6	161.1 ± 54.8	151.7 ± 43.4	174.2 ± 46.5*#
Isokinetic								
Concentric								
60°/s	138.6 ± 55.3	152.8 ± 64.9	151.1 ± 46.5	172.0 ± 55.2*	151.2 ± 64.3	160.4 ± 52.8	134.2 ± 27.7	149.1 ± 35.3
120°/s	105.8 ± 60.6	134.0 ± 64.5*	138.1 ± 47.7	152.6 ± 45.5*	134.7 ± 52.2	142.7 ± 51.1	107.1 ± 42.1	122.0 ± 38.6
Eccentric								
60°/s	205.0 ± 58.9	208.4 ± 90.0	199.1 ± 69.4	247.6 ± 85.8*	204.9 ± 78.1	217.0 ± 70.9*	190.4 ± 53.8	211.7 ± 55.6
120°/s	213.4 ± 61.8	222.3 ± 73.8	198.5 ± 68.3	243.0 ± 81.9*	194.1 ± 71.0	220.1 ± 75.1*	185.6 ± 46.1	194.9 ± 65.7
Acceleration time (ms)								
Concentric								
60°/s	111.5 ± 25.0	100.1 ± 17.4†	101.1 ± 10.6	95.7 ± 14.4†	92.0 ± 9.7	96.0 ± 10.5	91.0 ± 16.6	103.2 ± 15.1*
120°/s	123.2 ± 27.5	111.1 ± 23.0*	101.5 ± 16.4	104.3 ± 19.9	94.2 ± 8.3	95.4 ± 13.7	102.7 ± 30.8	114.9 ± 27.1
Eccentric								
60°/s	139.0 ± 19.3	120.4 ± 23.8*	113.9 ± 18.6	123.5 ± 14.6‡	103.2 ± 23.4	121.4 ± 24.9*‡	130.0 ± 43.1	133.9 ± 27.2
120°/s	168.4 ± 26.7	155.9 ± 35.2	145.6 ± 30.8	149.9 ± 19.4	136.0 ± 35.5	160.6 ± 34.4*	161.0 ± 58.0	178.1 ± 50.6

* $p < 0.05$, compared with pre-test values within group.
\# $p < 0.05$, compared with post-test values in LFV group.
† $p < 0.05$, compared with post-test values in CON group.
‡ $p < 0.05$, compared with post-test values in HFV group.
Abbreviations: CON = control; HFV = high frequency and low amplitude; LFV = low frequency and high amplitude; MFV = medium frequency and medium amplitude.

amplitude over the limitation of the WBV training platform for the MFV and LFV groups; the amplitude for the HFV group was chosen to be 1 mm. Therefore, the calculated acceleration load (4 *g*) was applied to each group for the entire 8-week WBV training period. The frequencies for the MFV and LFV groups were set at 18 Hz and 3 Hz, respectively, with the larger interval and arithmetic progression.

The results of this study showed that all settings could enhance either the muscle strength or the power of the knee extensors, but different settings led to different training effects of muscle contraction. The HFV group significantly increased strength of isometric contractions and 120°/s isokinetic concentric contractions; the LFV group significantly increased strength of 60°/s and 120°/s isokinetic eccentric contractions; and the MFV group significantly increased strength of 60°/s and 120°/s isokinetic concentric and eccentric contractions. The tonic vibration reflex was widely considered the mechanism that induced the effects of WBV training; in this test the length of muscle was changed rapidly and involuntarily by the vibration stimulation.[23] The sensitivity of stretch reflex was increased by the stimulation, then the excitation of the neuromuscular system caused more involuntary muscle contractions.[11] Although the CON group increased strength of isometric contractions as well after the 8-week isolated squat training without vibration stimulation, there was a negative effect on muscle power, which showed increasing trends for all acceleration times.

A previous study that used similar settings in the HFV group indicated that WBV training could enhance the strength of isometric contractions to 100°/s isokinetic concentric contractions of the knee extensors and CMJ performance in untrained women.[24] Other studies also illustrated that WBV training improved the angular velocities from 0°/s to 150°/s of the knee extensors[25] and isokinetic strength in postmenopausal women.[26] As in earlier studies, this study showed that after undertaking the 8-week WBV training with high frequency and low amplitude, young people could increase the strength of isometric contractions and 120°/s isokinetic concentric contractions. In addition, all the acceleration times showed decreasing trends in the HFV group compared with the other groups and were statistically reduced for low (60°/s) isokinetic eccentric and isokinetic concentric contractions as well as for high (120°/s) isokinetic eccentric and concentric contractions. This result was similar to another study, which showed that vibration stimulation could enhance the CMJ performance.[27]

The LFV group, with the same acceleration load as the HFV and MFV groups, had a significant increase in the strength of 60°/s and 120°/s isokinetic eccentric contractions but a decrease in the strength of isometric contractions. A low-frequency (3 Hz) and high-amplitude (114 mm) setting was used for a larger passive range of motion of the knee joints. The participants' muscles performed both concentric and eccentric isokinetic contractions in a passive, rapid, and repetitive manner when the platform was moved up and down rapidly by an electric motor.[20] The combination of eccentric and concentric contractions formed a stretch-shortening cycle, which could induce a stretch reflex and store elastic energy as vibration stimulation, to produce greater strength during the following concentric contractions and to enhance CMJ performance significantly.[28] Different types of muscle contractions resulted in different recruited patterns in the motor units and mechanisms of motor control, and chronic muscle strength training allowed the neuromuscular system to develop adaptability to certain types of contraction.[29] Although the vibration protocol with higher frequencies (>35 Hz) could significantly improve the performances of squat jumps and CMJ, it did not significantly change the eccentric utilization ratio.[30] In this study, the increase of eccentric contraction strength in the LFV group was higher than the effects of concentric and isometric contractions because of a high amplitude of passive stimulation.

Only the MFV group, for which moderate settings were used for frequency and amplitude in WBV training, significantly increased the strength of all low and high isokinetic concentric and eccentric contractions. In addition to isometric strength and CMJ performance, previous studies also proved that both acute vibration stimulation and chronic WBV training would enhance the isokinetic strength of muscle contractions.[31–33] A frequency of WBV training below 20 Hz should be avoided because of resonance within the human body,[34] but the transmission of vibration to the head can be reduced when the knees are semiflexed during WBV training.[35] In this study, participants were asked to perform dynamic squats on the vibration platform, and no participant reported discomfort during the 8-week training period. Therefore, the head discomfort could be prevented by a squatting position if the frequency of WBV training was set around 20 Hz.

Numerous studies in recent years have focused on exploring the best frequency and amplitude setting for WBV training, and most of the results suggested that higher frequencies and greater amplitudes could achieve better training effects.[8,21,32] The possible reason was that higher frequencies and/or greater amplitudes increase muscle contraction speed and/or change muscle lengths.[24] Although continuous high-frequency (40 Hz) vibration stimulation would cause acute fatigue and decrease the CMJ performance,[9] chronic high-frequency vibration stimulation could enhance the muscle power as a result of neuromuscular adaptability. A previous study indicated that the muscle tension influenced the recruitment order of slow- and fast-twitch alpha motor units.[36] In this study, all 3 frequency and amplitude settings could induce muscle tension. The results proved that the high-frequency and low-amplitude setting could increase muscle strength and power during isometric and high concentric contractions, whereas the low-frequency and high-amplitude setting improved muscle strength during eccentric contractions. The medium frequency and amplitude setting might efficiently stimulate and change the length of the muscle spindle, thereby increasing muscle strength during slow and fast isokinetic concentric and eccentric contractions. We suggest that future studies should explore whether various settings of frequency and amplitude would result in different stimulations of muscle tension and frequency responses to confirm the neuromuscular adaptability of vibration stimulation.

5. Conclusion

Eight weeks of WBV training could indeed increase the muscle strength and power of the knee extensors. However, various frequency and amplitude settings resulted in different chronic training effects, even under the same controlled acceleration. To enhance the strength of isometric and high isokinetic concentric contractions or the power, the WBV training should be set for a higher frequency and lower amplitude setting; to enhance the strength of eccentric contractions, the WBV training should be set for a lower frequency and higher amplitude setting; and to enhance the strength of both low and high isokinetic concentric and eccentric contractions, the WBV training should be set for a moderate frequency and amplitude setting. Furthermore, the squatting position should be used to prevent head discomfort during WBV training. Most commercial WBV training platforms only allowed users to adjust the frequency, but based on the results of this study, the function of adjustable amplitude should also be considered in developing new models to extend the application of WBV training in muscle strength or power training.

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Authors' contributions

TYS, LC, and YL carried out the genetic study and its design; HW and CL participated in the acquisition of data, statistical analysis, and drafted the manuscript; PC revised the critical manuscript. All authors have read and approved the final version of the manuscript, and agree with the order of presentation.

Competing interests

The authors declare that they have no competing interests.

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